AN ISENTROPIC ANALYSIS OF A THUNDERSTORM SITUATION

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by

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Department of Aeronautical Engineering, May 18, 1939

Signature of Professor
in Charge of Research ______________________

Signature of Chairman of Department
Committee on Graduate Students ______________________

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DENHAM, W.

May 15, 1939

Professor George W. Swett,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts

Dear Sir:

We are submitting herewith a thesis entitled "AN ISENTROPIC ANALYSIS OF A THUNDERSTORM SITUATION" in partial fulfillment of the Requirements for the Degree of MASTER OF SCIENCE in Aeronautical Engineering.

Yours respectfully,

Walter S. Denham

Denys W. Knoll

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I. INTRODUCTION

Early in January 1939 a thunderstorm situation developed over the Gulf states of the United States. A synoptic meteorologist who depended entirely upon surface map analysis would have experienced great difficulty forecasting this particular situation. The surface data which was available did not in itself present a clear concept of the processes which were occurring in the atmosphere. The weather which ensued could scarcely have been predicted with a reasonable margin of accuracy. It is the purpose of this paper to investigate this unusual weather situation and study in detail all the upper data with the objective to find some clues as to the causes of the thunderstorms which developed. Further an attempt will be made to describe any indications from which it would have been possible to predict thunderstorm developments. A better knowledge of the more intricate processes of the atmosphere will facilitate more reliable predictions and are only obtainable from a closer scrutiny of the upper air data as it is made available for each situation. The period covered is January 2-4 (inc.) 1939.

In order to investigate and coordinate the upper air data with the surface map analysis the following routine procedures have been employed:-isentropic charts,

representative vertical cross-sections of the atmosphere, Rossby Diagrams, adiabatic charts and pressure change maps for the surface conditions. In addition, the 8 A.M. surface maps and the 8 P.M. surface map for the 3rd have been included.

II. GENERAL WEATHER SITUATION

A brief description of the weather situation will be presented which will be further supplemented when the detailed day-by-day analysis is made in conjunction with the upper air data. Our main interest is centered in the south Central States, namely, Oklahoma, Arkansas, Mississippi, Louisiana and Texas. In this area a region of frontogenesis began to develop on the 2nd (#1), which developed into two secondary waves on the 3rd of January(#2).

The general weather situation on the morning of January 2 (#1), serves as an introduction to the phenomena investigated. In the northeastern part of the United States there exists an invasion of Pc air, which is supplanting Npc air and a narrow band of Npp air mass adjoining the Bermuda High; into this Npc air mass Tg air has begun to advance northeastward from the West Gulf region. A zone of frontogenesis is becoming apparent with a weak frontal region between the Npc air and a Npp air mass lying over the southwest. In the northwest Pp air has begun to penetrate to and including the Rocky mountains.

The cyclogenesis which commences in the northern part of the Texas panhandle near Amarillo, stagnated in this region for more than twenty-four hours. This disturbance developed first as a wave in the frontogenetic zone. The

The A.M. surface map of 3 January (#2) shows this disturbance deepening as a typical secondary extratropical cyclone and on 4 January (#4), it began to undergo occlusion. The advance of the warmer moist Tg air at the surface is indicated by the dew points on January 3 (#2), just south of Abilene and Dallas, Texas. The morning of 3 January (#2) presents a good example of the formation of a secondary disturbance as the result of a wave on a quasi-stationary cold front. The pressure tendencies in all sectors of the cyclone are negative and thus it appears the disturbance is still deepening. This deepening continues to be indicated on the P.M. surface map (#3), and the Tg air has advanced into southern Oklahoma.

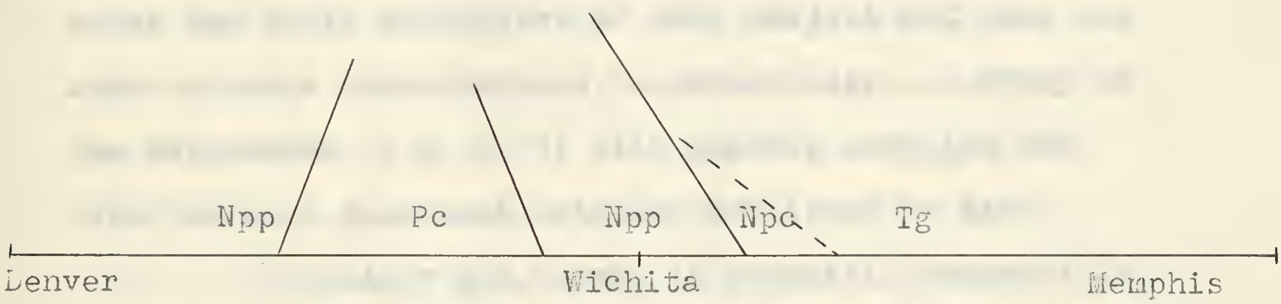
An additional feature to be noted on January 3 (#2) is the appearance of a weak cold front in the vicinity of Des Moines, Iowa, Omaha, and North Platte, Nebraska. This is the frontal zone between the Pc air in the northeast and the Npp air in the southwest. Twelve hours later (#3) this front has advanced 125 miles farther to the southwest and is now acting with its Pc wedge as a barrier to the advance of Pp air from the northwest and in like manner retards the advance of warm Tg and Npc air from the south and southeast. The advancing Pp air from the northwest appears to possess an upper level cold front associated with the warm front type occlusions, which are characteristic of Pp air advances from the northwest in winter.

The surface map for the morning of 4 January (#4) presents the conditions which contributed to the thunderstorm developments and at the same time encouraged further investigations as to their probable cause. The cold front which separates the Npp air in the southwest from the Tg flow of air out of the Gulf of Mexico has advanced eastward about 150 miles during the night as a more active cold front. It is located along a line through San Antonio, Forth Worth, Tulsa, and Eastern Kansas. Simultaneous with this advance thunderstorms occurred during the night over 300 miles in advance of the cold front. The thunderstorms which occurred, for example, at Nashville, Little Rock, and Monroe, Louisiana, were accompanied by heavy precipitation. The storm at Monroe occurred about 4 A.M. and lasted one hour with 1.83 inches of rain. The cold front was at this time more than 300 miles to the westward.

The upper level cold front of the previous analysis (#3) can no longer be located on the morning of the 4th (#4). The occlusion in the southwest had advanced southward and joined the cold front and exist as a single cold front over New Mexico and Arizona.

It is particularly noteworthy that the thunderstorms did not occur with any regularity in regard to front and neither can they be identified as air mass thunderstorms

since it is remarkable there are no indications of storms in the midst of the Tg air flow where it crosses the Gulf Coast at Mobile and Pensacola. A surface analysis does not explain these phenomena.



This sketch illustrates a cross-section of the complicated frontal structure on the 4th of January (#4) when a line is followed from Denver, Colorado, to Wichita, Kansas, to Memphis, Tennessee. An analysis of the upper air data is the one recourse which a synoptic meteorologist can choose, in order that he may ascertain what has been occurring since the previous map analysis and thereby make a reasonable prediction of the future weather.

III. A BRIEF DISCUSSION OF ISENTROPIC ANALYSIS

A detailed description of isentropic analysis is not deemed necessary at this time. In the past few years many articles have been published which completely cover the basic principles of this subject and they are also valuable contributions to meteorology. A study of the references (, 3, 6, 7) will quickly acquaint one with the more important articles published to date.

Professor C.G.Rossby is primarily responsible for the development of isentropic analysis. A somewhat similar application was suggested by Sir Napier Shaw (Vol. III, Physical Processes of Weather 1933) but Professor Rossby and his collaborators (1) developed the technique and introduced isentropic analysis into daily synoptic practice. Professor Rossby has also indicated that isentropic charts are the logical and independent outgrowth of a study of lateral mixing in the atmosphere.

As mentioned by Byers (8) the isentropic chart serves a twofold purpose as a hydrodynamic and a thermodynamic chart -- hydrodynamic in the sense that the paths of "tongues" of maximum water-vapor content serve as identifying indicators of the flow pattern and of lateral mixing; and thermodynamic with respect to indications of adiabatic changes in the air, including water-vapor, as it flows along

the sloping or broadly undulating surface.

The isentropic chart is usually drawn to represent a contour map of an isentropic surface with isograms of specific humidity along the same surface superimposed. Additional data such as winds, relative humidities, clouds, etc. are entered at the points of observation. Pressure and altitude are closely related, which makes it preferable to use isobars in place of elevation contours on the charts. The procedure at Massachusetts Institute of Technology makes use of specific humidities instead of the isentropic condensation pressures used by Byers. It is recognized that the condensation pressure along an isentropic surface has only one value for each specific humidity. It is questionable if the advantages of this procedure are sufficient to warrant its universal adoption. In the present investigation the procedures advocated by the Massachusetts Institute of Technology are recognized as standard and are followed throughout.

The addition of the values of maximum specific humidity for each isentropic-isobar has been recommended and used by Namias. These are indicated in parenthesis adjacent to the isobaric designation. The areas of condensation are thus readily recognized where the actual values of specific humidity approach or equal the values

the slopes, as steeply descending currents.

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The analysis of the charts of constant specific humidity for each isentropic surface was then undertaken, supplemented by winds. These are indicated by isentropic patterns of the isentropic variation. The areas of the isentropic dry tongue, especially the areas of the extent of specific humidity lines, are shown by the values

of maximum specific humidity of the isobaric surface.

The subsequent analysis of the upper air data follows the standard routine now employed in daily synoptic work.

IV. UPPER AIR ANALYSIS OF THE SITUATION

The surface conditions for the period concerned have been fully described in Chapter II. In that chapter it was concluded that a surface analysis alone does not explain the phenomenon of the nocturnal thunderstorms. Therefore, an attempt will be made to utilize the upper air data in such a manner as to explain the occurrence of the thunderstorms; and, if possible, by such explanation to furnish a method for forecasting them in similar situations.

By use of the data gathered from the various aerological stations, it has been possible to construct the accompanying cross-sections, isentropic charts and diagrams.

Now, the cross-sections and isentropic charts are constructed from the data furnished by individual ascents; and to emphasize the advantage of isentropic analysis, as well as to discover the characteristics at the various stations, a discussion of the individual soundings is suggested before proceeding with the discussion of the charts.

Soundings of 2 January

The sounding at Oklahoma City can be taken as fairly typical of conditions in the western part of the

forming warm sector. The Rossby diagram (#31) shows the air mass to be in good agreement with Willett's values for Npc. Convective instability from 942 to 893 millibars is disclosed by this diagram. Inspection of the adiabatic diagram (#19) discloses the convective instability to be due to a rapid decrease in moisture, since the lapse rate is less steep than the moist adiabat. The very sharp inversion at the ground, 12° in 250 meters, is undoubtedly one formed by radiation. This radiation must have been particularly intense since at the time of the sounding a surface wind of 5.4 meters per second is reported. The small values of relative humidity aloft indicate the probable reason for such pronounced cooling at the ground.

The high temperatures above the inversion and the low relative humidities definitely suggest that subsidence of some magnitude has occurred in the anticyclone. This subsidence must have been accompanied by divergence as particularly emphasized by Namias (8). The surface map suggests convergence between the Npp and the Npc anticyclones. However, both the highs are seen to be lessening in pressure at the center and to be spreading out over a larger area, accounting thereby for the divergence aloft.

An interesting feature of this sounding is the

0.7° temperature inversion between the levels of 712 and 686 millibars, immediately above a stratum with an adiabatic lapse rate, suggesting turbulence and a resulting inversion.

The Omaha sounding (#32) is in good agreement with the values as given by Willett for Npp, temperatures and specific humidity showing close agreement.

The existence of Npp over the Npc high is established by inspection of the Nashville sounding (#33), specifically by comparing the potential temperature and the moisture content at the 771 millibar level, with the values at Omaha for that pressure; and, further, by the parallelism of their curves on the Rossby diagrams.

An outstanding fact shown by the above mentioned diagrams is the lack of contrast between the air masses involved. The classical concept of frontogenesis is that of convergence between the two air masses of contrasting properties; the lines of flow being perpendicular to the isopleths of temperature and/or humidity. In this situation comparison of the characteristic curves at Omaha, Nashville, and Chicago would lead to the conclusion that no important front would develop, and there would be no pronounced cyclogenesis.

3 Kilometer Map, 2 January

Inspection of this map shows the flow at this

level to be almost exactly zonal, from the Rocky Mountains eastward. The winds at all levels aloft show this same latitudinal transport except for stations west of North Platte and the southerly winds reported at Del Rio and San Antonio, Texas, which persist to 3 km. The southerly winds reported by Pacific coast stations are referred to for comparison with conditions on the following days.

Soundings of 3 January

On the adiabatic diagram (#20) for Oklahoma City on this date, a wet bulb curve has been constructed for comparison of stability conditions on this day and the following day. This curve is particularly useful for determining the amount of lifting necessary before autoconvection will result; and further how large a layer possesses such latent instability. Inspection of the curve shows no latent instability for lifting within the limits of the sounding, this despite an adiabatic lapse rate from the 728 to 646 millibars. The temperature has increased slightly since the preceding day from the surface to about the 600 millibar level by an average amount of 2°C. Above that level, temperature shows practically no change. Simultaneously, the moisture content has increased from the surface to practically the top of the sounding. These changes contribute to the possibility

of shower formation; but, as yet are by no means threatening.

The small inversion of 0.7°C. noted on the second is to be associated with the similar one from 650 to 628 millibars on this date.

The Nashville sounding shown on (#21) and (#33) shows similar striking stability conditions. Omaha is overlain by air with very stable characteristics as can be seen from the sounding plotted on #22 and #32.

El Paso, on this date, furnishes no information as to the threat of instability, or no warning that moisture is about to be introduced in large amounts.

The Rossby diagram #30 has been constructed to show the lack of significant contrast between the air masses present, less than twenty-four hours before the outbreak of violent convective activity. It may be remarked at this point, that, were there a station well south of Oklahoma City which could have furnished a sounding at this time, that sufficient contrast could have been discovered to account for the subsequent development. In this connection, it is to be particularly noted, however, that only three stations in the western part of the warm sector, where Npc is at the surface, report any clouds. Further, that as late as 8 p.m. only four stations ahead of the Tg front report 10/10ths cloudiness to indicate advance of moist air.

3 Kilometer Map, 3 January

This map shows, in the region under consideration, a very slight change from westerly winds to winds slightly south of west. However, a change of utmost importance is observed on the Pacific Coast. The winds at this level which on the preceding day were southerly have turned to westerly directions. The effect of this turning of the winds west of the Rockies is believed by the authors to have a very important bearing on the events to follow and will be considered in detail under "Inferences from the Isentropic Analysis". The anticyclonic circulation over Colorado, Utah, Arizona, and New Mexico has been replaced by cyclonic curvature of the isobars. Further north the isobars remain westerly.

Soundings of the 4th

These soundings, though retrospective as far as the occurrence of the thunderstorms is concerned, are discussed to emphasize the magnitude of the changes which have been effected since the morning of the third.

For Nashville the Rossby diagram (#33) shows a tremendous increase of moisture at all potential temperature surfaces, with a maximum at the 295° surface. This inversion of moisture may be taken as marking the

base of the warm current as suggested in Namias (8). There is no convective instability from the 922 to the 645 millibar levels, or about three kilometers possess such instability. As is strikingly evident from the latent instability shown by the wet bulb curve of (#25) free convection of a layer of more than two kilometers would result on a lifting of the order of thirty meters; such free convection could then proceed to at least as high a level as the top of the sounding. Given such a sounding the imminency of a thunderstorm is most apparent. The most important feature of this sounding is the fact that above the level of 825 millibars the temperatures at all points are less, by about three degrees, than on the preceding day, while at the same time temperatures below this level have all increased by an average of four degrees Centigrade. At the same time, the moisture content at all levels has increased during the period. This increase is more marked at the lower levels than aloft.

For both comparison and contrast the sounding at Oklahoma City (#27) is now referred to. As at Nashville the moisture at all levels has increased. But, the magnitude of this increase at lower levels is much less. Further, near the surface there has been an increase of temperature, and above 900 millibars there has been an increase. Yet the wet bulb curve reveals that no free convection could

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result without lifting to the 500 mb. level, too high for consideration. The result is that Oklahoma City reports, at 8 a.m., clear skies and no precipitation during the preceding twenty-four hours. This despite the fact that a cols front has passed the station during the preceding four hours; as evidenced by a drop in dew point from 49°F to 34°F.

The sounding at Omaha (#28) discloses latent instability from the 900 to the 785 millibar levels. TThe temperature since the preceding day is less at all levels.

Contrasting to the Nashville and Omaha soundings, the conditions at Pensacola are seen in (#26) to be quite stable.

3 Kilometer Map, 4 January

The outstanding feature of this map is the extensive trough of low pressure centered at about North Platte. Where on the third, over the Rocky Mountains, there were westerly winds, there are now strong winds with northwesterly components. East of the trough south westerly winds of force nine and ten are reported. The reason for this trough formation will be more fully discussed later, when an attempt will be made to explain the forecasting significance of the change observed on the Pacific coast on the third.

Resume of the Soundings

The soundings from the aerological stations available as analyzed gave no evidence of any considerable increase in instability, from the second to the third. The air masses involved in the zone of convergence showed little contrast; except at the ground where good contrast between the Tg and the Npc was evident. The Tg air at the surface extended in a broad band from west of Abilene to east of Pensacola at the time of the p.m. observation of the third. However, few clouds indicating overrunning, hence, advance of the Tg, were reported.

The Isentropic Analysis

Cross-sections of 2 January

The Fargo-Oklahoma City section (#35) shows a concentration of moisture near Fargo in the form of a bubble, the source of the moisture being separate from that of the intruding moist tongue at Oklahoma City. A similar concentration of moisture between Chicago and Nashville is evident on the Sault Ste. Marie-Nashville section. A moist tongue at Oakland is shown entering on the west-east section (#34). The concentration of moisture at Spokane on the Spokane-Billings section is, as will be seen from the isentropic chart, to be identi-

fied with the moisture at Fargo.

The 295° Surface

Conditions are as indicated on (#8). This shows the extremely long moist tongue of Pacific origin extending from North Dakota east south eastward and recurving cyclonically near Washington, D.C. under the dominating influence of the dry tongue of cold Polar air. It is to be expected that this dry flow will shut off the flow of moisture from the Pacific, and seclude the advance portion of the moist tongue.

Stagnant, and relatively dry cold air appears as a large anticyclonic eddy over the plateau states, flanked by two moist tongues. Lateral mixing will gradually cause the disappearance of this dry eddy. Of interest are the strong winds at Havre, Mont. and Spokane, Washington. They are probably super gradient and due to excess of Corlioli's force will result in convergence or piling up of air to the right. Due to the amount of time available this assumption was not able to be verified; but whether or not it is valid will be determined by the authors.

The tongue of moisture observed over Oklahoma City confirms the concentration observed there on the Fargo-Oklahoma City cross-section. This tongue would be

even more pronounced on a 290° potential temperature surface.

Cross-sections of 3 January

The Spokane-El Paso section (#40) shows increased separation of the 295° and 300° potential temperature surfaces between Salt Lake City and El Paso. This increased separation means lessening of stability. This separation is evidently due to the strong winds at Spokane and Billings on the second, mentioned previously.

The north-south cross-sections (#39) show stabilization of the lapse rate at the lower layer, in that the potential temperature surfaces are closely packed. Most significant is the moist tongue coming from the southwest. The dipping of the potential temperature surfaces indicates the advection of warmer air.

The Oklahoma-City-Norfolk section repeats the moist tongue features mentioned in the last paragraph, and indicates further, that conditions are becoming less stable, though little so, in that the isentropic surfaces show slight signs of increasing vertical separation.

The 295° Surface

The feature of major importance and therefore of greatest interest is the tremendous increase since the

second of the winds in the moist tongue, lying just east of Oklahoma City. This fact suggests more rapid transport of moisture than previously, as well as the advection of moister air. The height lines, in the region of the Great Lakes, give a clue to the steep slope of the cold air. This deep cold dome coupled with the rapid advection of warm moist air will furnish sharp contrast in the elements. The dry eddy over northern Florida is seen to have anticyclonic circulation in response to the dominant moist tongue to its west.

The shutting off of the moist flow from the pacific, by the cold, dry air, near Norfolk is in agreement with past experience with isentropic analysis.

The dry eddy over the plateau persists, but it will be noted that its area is considerably diminished, indicating the mixing at the boundaries.

The moist tongue of Ntp over the west coast is seen to have winds of far less magnitude than the tongue first mentioned.

The 300° Surface

As in the 295° surface the flow of moisture towards the north is seen as a tongue over Texas and western Arkansas. In it, as in its lower counterpart winds of whole gale force are reported. The surprising

feature of this tongue, however, is that its axis lies some 150 miles to the east of the axis in the lower surface. This implies that large moisture contents in the lower layers does not necessarily mean convective showers can occur. Also, it has the implication, that unlike surface cold fronts the dry air is found further eastward with increasing elevation.

In consonance with this condition, the dry eddy just west of this moist tongue is seen to be centered further east than the eddy in the 295° surface. Further, the area of the dry eddy is larger in this surface than in the lower, implying a narrowing of the moist tongue.

A similar tilt of the axis of the westernmost moist tongue is found.

It is not known if the tilt of the axes with increasing potential temperature is inherent in moist tongue. The occurrence is not known to have been reported previously.

The 305° Surface

In this surface, the outstanding feature is the further eastward displacement of the moist tongue axis and of the dry eddy center. Diversion of the main moist tongue to a more easterly trajectory is indicated by the

turning to the westward of the winds north of Oklahoma City.

At this point particular attention is called to the height of the surface at El Paso, 655 millibars; and to the specific humidity 1.5 grams.

Cross-sections of 4 January

The Oklahoma-Norfolk section (#44) illustrates graphically the globular shape of the moist tongue. The sloping of the specific humidity lines downward on each side shows the narrowing of the tongue with altitude in graphic manner. The instability is strikingly demonstrated by the separation of the potential temperature surfaces at Nashville. This could not be the result of previous convection because the 305° surface bulges upward, not dipping down as would be the case with convectionally transported heat. The 295° has been lowered since the previous day, but this the result of advection of warm air. The rise of the 305° surface could hardly be attributed to radiation since the moisture in that surface has increased since the previous day, not decreased, as would be expected following intense radiation aloft.

The 295° Surface

The moist current of principal interest has been divided into two branches. This branching can be

attributed to the circulation around the now deep cyclone as a result of solenoidal formation, one part responds to this circulation, while the part of the tongue more remote preserves its anticyclonic verticity. Specific humidities in the moist tongue have increased tremendously since the previous say, as far as north as Fargo the specific humidity is greater than any values reported in the surface on the third. This spread of moisture is undoubtedly due to the strong winds which have prevailed in this tongue. It will be observed that the westernmost moist tongue which on the third did not possess such strong winds as the former, has now shrunk in intensity to the point as to no longer be of significance. Simultaneously the dry eddy between the two tongues has almost totally disappeared by mixing processes.

<u>The 300° Surface</u>

This surface exhibits a diverging moist current over the southeastern states like the 295° surface, and near the axis possesses a moisture content almost as high as those observed in the lower surface, but with the difference that it has a much larger lateral moisture gradient. Both branches are seen to lie to the right of the positions of the branches in the lower surface; as was noted on the previous day.

The polar tongues of dry air are seen to cover a much larger area than the corresponding tongues occupied in the lower layer, with the result, that the moisture which attained the latitude of Fargo by the original impetus has been cut off from its source by the spreading dry air.

The 305° Surface

Very similar differences between the position of the axes and centers of tongues and eddies in this and the 300° surface are noted as between the position in the latter and in the 295° surface.

The temperature in this surface over Nashville is seen to differ considerably from that at Pensacola by the height lines intervening between these stations.

Comparison of the areas of dry and moist tongues illustrates, in striking manner, the comparative narrowness of the moist tongues in the higher potential temperature surfaces.

The height of this surface at Nashville is particularly to be noted, i.e., 645 millibars. Further, the moisture content is seen to be 3.8 grams.

INFERENCES FROM THE ISENTROPIC ANALYSIS

The rapid injection of warm moist air into the zone of surface convergence could have been forecast because the strength of the winds in the moist tongue clearly indicated that it would be a dominant feature of the pattern of the isentropic surface. The increase of the winds in the 295° surface between the second and the third may be attributed to the formation of solenoids between the warm moist air and and the colder air to the westward. It is possible that this may not be the case; in fact, the winds might have been evident at an earlier date further south. The upper winds for the southern Gulf and Eastern Mexico were not available, at the time of this article but an attempt will be made to see if such was the case. In any case, once winds of such strength are observed in an intruding tongue of moist air it seems most reasonable to conclude that there will be correspondingly rapid advection of moister and moister air. At the same time, due to their direction more and more heat will be introduced into the region to which the flow is directed.

As to where the moisture will be transported, it is seen that the tongue has anticyclonic curvature in consequence of conservation of vorticity. Hence, barring

strong external forces it will continue with such anti-cyclonic curvature.

The extreme narrowness of the tongue accounts for the restricted band of precipitation observed during the night of 3-4 January, despite the uniformity of surface conditions in the broad advancing Tg sector. Quite possibly an isentropic analysis of the situation analyzed by Emmons (9) would reveal the reason for the pattern of rainfall observed during the night of 30-31 December, 1929.

Now the advection of moisture and heat in the lower layers does not explain the pronounced instability obderved at Nashville on the morning of the fourth, and which must have been present at the stations where other nocturnal thunderstorms were reported.

Humphreys (8) lists as reasons for the production of convectional instability: a) Strong surface heating, b) Overrunning of one layer of air by another at a temperature sufficiently lower to induce convection, and c) Underrunning and consequent uplift of a saturated layer of air by another more dense layer. To these possible causes must be added d) Overrunning of a dense layer by convectively unstable air, i.e., warm front thunderstorms, e) radiation from aloft as suggested by Namias (7) and (f) convergence.

The strong surface heating may at once be dismissed.

The underrunning of a saturated layer by a denser layer could possibly be the explanation of the thunderstorms at Austin, Texas ans Chanute, Kansas. But, such lifting could not apply to the heavy precipitation reported at the other points in the warm sector.

Radiation from aloft might lift isentropic surfaces but would not increase the moisture content in a particular surface. The surface is in fact not lifted; it is merely found at a higher level for an atmosphere with a lapse rate less than the super-adiabatic, and normally moisture decreases with elevation.

Convergence, as is well known, tends to steepen the lapse rate. But, in this situation no pronounced indication of convergence is indicated.

There remains the overrunning of colder air, other possibilities having been eliminated. The effect on lapse rates of such overrunning has been fully discussed by Rossby and Weightman (4). To show that this was the case and that it logically followed from previous events the turning of the winds clockwise through 90° on the Pacific Coast between the second and the third at the level of three kilometers. As suggested by Professor Rossby, this turning of the winds west of the Rocky Mountains, in accordance with the theory of conservation of vorticity, should result in a similar turn-

ing of the winds eastward of these mountains at a later date. Further, that these winds to the east in virtue of the westerly components on the western side will have a more northerly direction than formerly because of the anticyclonic curvature imparted in the ascent to the crest, and resultant straightening of the lines of flow in descending. Exactly this type of flow is noted in the three kilometer map on the fourth of January. As the air flows southward, it will lead to a piling up against air which may have skirted the mountains to the southward and hence form a high. This in turn will lead to at first checking the southward flow and then redirecting it to the northward, thus forming a trough. This, then, is the explanation of the trough which appears, on the map referred to, on the fourth.

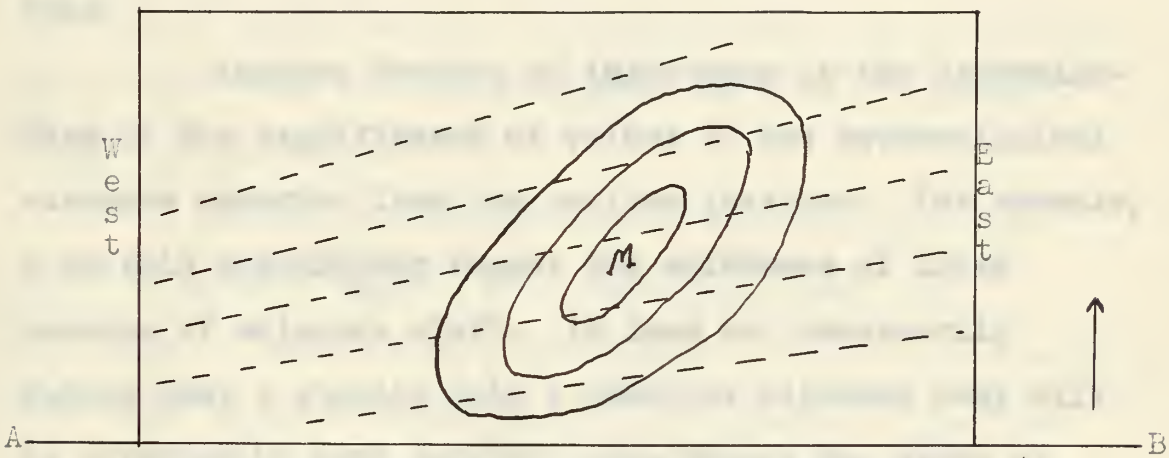
Now, on the morning of the third, the 305° surface was at the level of 655 millibars. The trough was at this time forming and the winds in it transported the cold air to the vicinity of Nashville, as evidenced by the fact that on the morning of the fourth the 305° surface lay at the pressure level of 645 millibars. The increase in moisture is not in excess of amounts to be expected with lateral mixing.

The isentropic charts show that the conditioning of the atmosphere for convective instability was

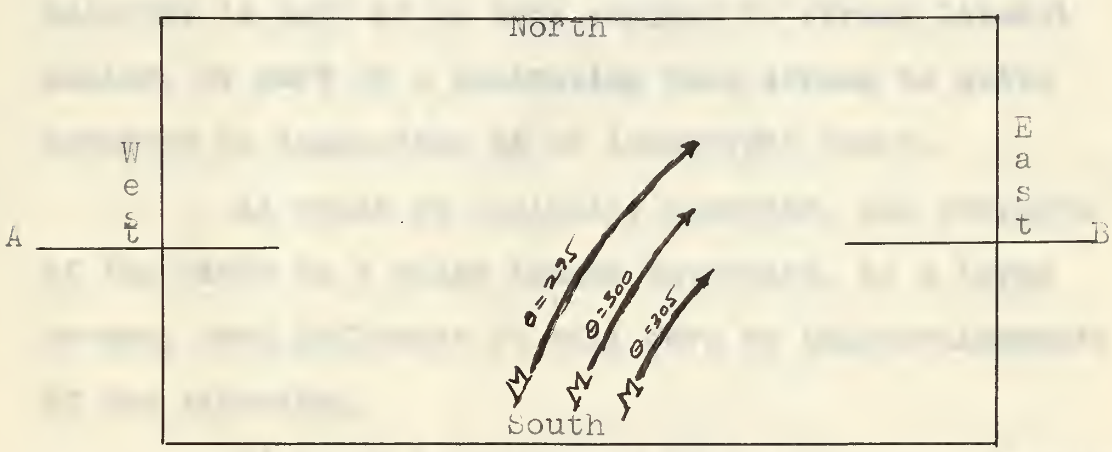
due to the advection of moist warm air at lower layers; simultaneously with the advection of much vclder air aloft, but with a sufficiently high moisture content to permit continued free convection. Excessive dryness at intermediate levels is generally recognized to have a decidedly drying effect on shower formation regardless of lapse rate.

V. SOME INTERESTING FEATURES OF THE ISENTROPIC METHOD OF ANALYSIS

Probably the most interesting feature disclosed by the isentropic analysis of the subject situation is the tilt of the axes from west to east, as indicated in accompanying schematic figures, of tongues



East-West cross-section of Moist Tongue through Isentropic Surfaces



Illustrating shift of axis of Moist Tongues in Isentropic Surfaces

and eddies with isentropic surfaces of higher potential temperature. Quite possibly this tilt can be ascribed to the increase in the westerly components of the wind with increasing elevation. This tilt may not be a feature of all situations. The authors are not aware of such tilt having previously been reported, possibly because relatively few situations have been analyzed with the aid of more than one surface of potential temperature.

Another feature of importance is the determination of the significance of values of the meteorological elements reported from the various stations. For example, a certain station may report the existence of large amounts of moisture aloft. It does not necessarily follow that a station only a moderate distance away will be affected by such moisture even though the winds at the former are directed toward the latter. Whether the moisture is part of an eddy subject to strong lateral mixing, or part of a dominating wake stream is quite apparent by inspection of an isentropic chart.

As would be logically expected, the strength of the winds in a moist tongue determine, to a large extent, what influence it will have on the developments of the situation.

Of great importance is the narrowness of moist

tongues, particularly noticeable in the higher valued surfaces. As a corollary the dry areas are seen to increase in size with elevation. This is not a wholly unexpected result since the normal condition aloft at this time of the year over continental areas is one of dryness due to temperature effects. Yet the determination of the width of a moist tongue is of the utmost importance in fixing the regions where they can be appreciable precipitation. This statement can be readily appreciated when the narrowness of the band of precipitation is considered.

Further the location of a moist tongue in a lower isentropic surface does not always show the formation of convectional instability. This is particularly true where slight frontal action is involved. The construction of higher valued surfaces of potential temperatures renders possible foreseeing advection of colder air, hence, gives a warning of threatening instability.

The isentropic isallobars (#45), 46, 47 and 48 were constructed with a view to determining the usefulness of such charts in forecasting significant changes in the lapse rates for later periods. As concluded by Namias (7) such isallobaric charts are not conclusive in their indications. Further it is seen that layers vertically adjacent may have experienced changes in thickness of

opposite sign in any one period. Quite obviously occurrences of a similar nature may explain the lack of correlation between the isallobars of a single layer and the surface isallobars as found by Namias in such comparison.

opposite side in any one period. Quite accidentally occurrence of a similar nature may explain the lack of correlation between the isolines of a single layer and the diffuse isolines, as found by Mantel in such comparison.

V. SUMMARY AND CONCLUSIONS

This investigation shows, as has been expected, that isentropic analysis possesses many facilities for studying situations, which other methods hitherto have failed to exhibit. Isentropic analysis to date has generally been confined to the study of single isentropic surfaces. This analysis illustrates the benefits to be derived from the use of two and three surfaces in conjunction with cross-sections in order to obtain a clearer concept of the isentropic flow of moist tongues. In addition, as has been previously mentioned, the determination of the moist tongue dimensions and the alignment of its axis can be of major importance for forecasting future conditions.

The benefits to be derived from isentropic analysis are many, but it is evident that continual practice in analyzing conditions is very necessary in order that a plausible analysis may result. A definite acquaintance with summer and winter patterns can only be acquired by daily practice. As the technique of the individual becomes perfected, the resulting forecasts should become more accurate. It is believed this method of analysis will merit greater attention in daily synoptic work, as soon as the greater proficiency is attained.

The preparation of a reasonable analysis requires a good deal of time, which to date has made this method impractical for use in the military or naval service. The personnel available for aerological duties are limited; and time is a valuable item during routine operations. The operations officer demands a forecast as soon as the surface map has been analyzed, so the preparation of material and personnel can be completed in ample time to accomplish their mission.

It is hoped that a suitable system can be devised, which will allow the service forecaster an opportunity to use isentropic analysis. The preparation of these charts at a central office by experts may be one solution. The charts can then be studied for salient features and the important data disseminated with an appropriate code via teletype and radio.

It is believed that the service meteorologists in general recognize the worth of isentropic analysis. It will find its rightful place in daily synoptic work when a routine has been devised to meet the exigencies of the service.

Greater accuracy in forecasting is one objective toward which every meteorologist is working. The one route to this goal seems to be a comprehensive study of aerological data and a definite application of it in

daily work. A series of morning and evening observations over the United States for an extended period may contribute valuable enlightenment concerning phenomena and controlling features not previously known.

The authors are quite convinced that aerological observations from a locality on the Gulf coast near Brownsville would have been of great assistance in the work undertaken. The continued advances of Tg air from this sector and the effect of this air on the weather of southeastern United States would seem to make continual observations from this territory of the utmost consequence. There is reason to believe that the new assignment of aerological observing stations will be an answer to this deficiency.

CONCLUSIONS

1. The situation was represented by isentropic analysis in a logical sequence of developments for the three days, whereas surface analysis alone did not.

2. As a corollary to (1) isentropic analysis will contribute greatly to the accuracy of forecasts.

3. The moisture patterns of the isentropic charts appeared to have their axes tilted from west to east, with increasing values of the potential temperature surfaces. Coincidentally the area of dry tongues and eddies increase in size with progression into higher valued surfaces.

4. The construction of more than one isentropic surface was necessary in order to explain the developments of the situation. It follows that for forecasting the developments in many situations that more than one isentropic chart should be constructed. The daily cross-sections can be employed for the determination of when such additional charts are necessary.

5. The appearance, in a tongue, of uniformly directed and relatively strong winds is very indicative that such tongues will play a dominant role in subsequent developments of the situation, hence is a good criterion for forecasting.

6. The isallobaric charts of isentropic layers cannot, as yet, be gainfully employed in isentropic analysis.

RECOMMENDATIONS

1. More aerological stations should be established to furnish a more complete picture of the processes at work aloft than is now possible. Such stations should be established in localities where dominating flows have been observed to most frequently enter the present networks.

2. The aerological observations should be made at least twice daily. If such a frequency of observation is not practicable throughout the year, there should be provision for taking them this often in selected situations for the purpose of research.

3. The technique of construction and interpretation of isentropic charts should be standardized to the extent that such charts can be made at central stations and a description of the features of the situation be broadcast to the various units. This procedure would secure the benefits of isentropic analysis to those units which may not have sufficient personnel to make the construction in a reasonable time.

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